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Slurry erosion behavior of high entropy alloys

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ABSTRACT

High entropy alloys (HEAs) represent a new paradigm of structural alloys comprising of multiple principal elements in equimolar or near-equimolar concentration. The superior corrosion and oxidation resistance of HEAs at high temperature make them attractive for several structural applications. In this context, erosion behavior of HEAs has been largely unexplored. In this study, the slurry erosion performance of single phase $Al_{0.1}$CoCrFeNi high entropy alloy was investigated. For comparison, mild steel and stainless steel (SS316L) were also investigated under similar conditions. The slurry erosion was conducted at different impingement angles and at a constant velocity of 20 m/s. The microstructural and mechanical characterization were conducted using scanning electron microscope (SEM), energy dispersive spectroscopy (EDS), x-ray diffraction (XRD), nanoindentation and micro-hardness testing. Similar to the mild steel and stainless steel, HEA also showed ductile mode of erosion. The erosion rate for HEA was found to be higher compared to stainless steel, however in spite of lower tensile strength and hardness, HEA exhibited higher erosion resistance compared to mild steel. The high erosion resistance of HEA compared to mild steel is explained on the basis of its work hardening behavior, low stacking fault energy, and superior corrosion resistance. Erosion response of the investigated materials showed significant correlation with ultimate strength and ultimate resilience. In depth analysis of the eroded HEA samples showed ploughing as the prominent material removal mechanism at oblique angles compared to micro-cutting for SS316L and mild steel. In contrast, highly deformed and work-hardened platelets were observed at normal impingement angle for all materials.

1. Introduction

Materials used in fluid machineries such as pumps, turbines, propellers and valves typically show surface degradation in the form of erosion and result in significant economic impact [1]. State-of-the-art materials used in these applications show limited resistance against wear, erosion, and corrosion. Therefore, advanced materials with superior surface properties are needed to counter these forms of degradation. Recently developed high entropy alloys (HEAs) with exceptional properties have shown promising results [2,3]. HEAs contain at least four to five principal elements mixed in equi-molar or nearly equi-molar fraction. The exceptional properties of HEAs are mainly attributed to four core effects: high configurational entropy, sluggish diffusion, lattice distortion and cock tail effect [2–4]. HEAs may also contain minor elements with atomic fraction less than 5 at%. The high mixing entropy is a dominant factor which influences the mechanical and tribological properties of HEAs [3]. The high mixing entropy in a multi-principal element system promotes the thermodynamically stable solid solution, which otherwise results in a brittle intermetallic phase [4–6]. The high mixing entropy is also responsible for exceptional high temperature properties of HEAs [6]. The structure of HEAs is mainly composed of simple face centred cubic (FCC), body centred cubic (BCC) and/or their combination, despite being accompanied by elements with different structures. The properties of HEAs are influenced and regulated by interactions among the constituent elements. Tung et al. [7] observed that increasing Al and Cr contents in AlCoCrCuFeNi, results in transformation from FCC to BCC phase, whereas, Co, Fe and Ni favours FCC. On the other hand, an increase in Cu content leads to the formation of Cu rich inter-dendrite structure due to the low mixing enthalpy with other constituent elements. Tong et al. [8] reported increased hardness and elastic modulus of Al_xCoCrCuFeNi HEA being related with the strong binding energy and large atomic size of Al. Wang et al. [9] reported an increase in hardness of Al_xCrCoFeNi with the addition of Al due to transformation of

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structure from FCC to BCC. The valence electron concentration (VEC) has also been observed to influence transition in the lattice structure [6].

Although limited, there are studies that have explored the wear and corrosion behavior of HEAs. Wu et al. [10] reported increase in wear resistance of $Al_xCoCrCuFeNi$ HEA with the addition of Al ($x=3.0$) mainly due to increased hardness. In addition, the wear mechanism changes from oxidation controlled to predominantly delamination wear. Chuang et al. [11] observed that $Co_{1.5}CrFeNi_{1.5}Ti$ and $Al_{0.2}Co_{1.5}CrFeNi_{1.5}Ti$ exhibited excellent wear resistance compared to conventional alloys due to higher resistance to oxidation and lower high temperature softening. For $AlCoCrFe_xMo_{0.5}Ni$ and AlCoCrCuFeNi, the wear resistance was remarkably higher due to the formation of harder sigma (σ) phase as a result of replacing Cu with Mo [10,12]. With further increase in Fe ($x > 1.0$), the hardness and wear resistance decreases mainly due to decrease in σ phase and higher oxidation rate [12]. Hsu et al. [13] reported an increase in wear resistance and high temperature compressive strength of $Al_{0.5}CoCrCuFeNiB_x$ with the addition of boron content mainly due to the formation of borides.

HEAs also showed high corrosion and pitting resistance compared to 304 stainless steel [14,15]. Zhao et al. [16] reported improved tribo-corrosion behaviour for annealed AlCoCrCuFeNi at high temperature compared to 304L stainless steel. Low mixing enthalpy of Cu with constituent elements in $Al_xCoCrCuFeNi$ leading to formation of Cu-rich interdendritic region resulted in increased wear rates and high corrosion rates due to galvanic action [8,10]. Replacing Cu with Mn in $Al_xCrFe_{1.5}MnNi_{0.5}$, Lee et al. [17] reported an increase in corrosion and pitting resistance. Further the corrosion and pitting resistance also increased with a decrease in Al content. Lin et al. [18] showed that segregation of Al-Ni rich phase leads to high hardness with nominal corrosion resistance of as-cast and aged $Al_{0.5}CoCrFeNi$ HEA compared to conventional steel. Ji et al. [19] showed $Al_3CoCrFeNi$ coating lowers the erosion rates of 17-7 stainless steel. Although there are limited number of studies on wear and corrosion behaviour of HEAs, their erosion behavior has been largely unexplored.

In the current work, slurry erosion behavior of $Al_{0.1}CrCoFeNi$ high entropy alloy was investigated. For comparison, two conventionally used structural materials, mild steel and SS316L stainless steel were tested under identical conditions. Despite lower hardness, the HEA exhibited higher erosion resistance compared to mild steel, which is primarily attributed to higher ductility and superior corrosion resistance.

2. Experimental details

2.1. Materials

The nominal composition of $Al_{0.1}CrCoFeNi$ high entropy alloy used in present work is shown in Table 1. The composition of mild steel (MS) and SS316L (SS) stainless steel used for comparison, is also shown. HEA alloy was prepared using induction melting followed by hot isostatic pressing (HIP) for densification. HIP was performed at 1473 K for 4 h at a pressure of 100 MPa, followed by cooling.

Samples of HEA, MS and SS of size $10 \times 10 \times 5\ mm^3$ were prepared from ingots using conventional machining processes followed by cutting on wire electric discharge machining (wire EDM). All samples were polished and grounded using abrasive papers down to 2000 grit size. Microstructural characterization of the samples was performed using electron backscatter diffraction (EBSD) and x-ray diffraction (XRD). Mechanical properties of the samples were measured using micro and nanoindentation. Elastic modulus of the test samples was calculated from the slope of unloading curve using Oliver-Pharr method. To avoid hardness and elastic modulus measurement from the single grain (especially for HEA), micro and nano indentations were performed on two different samples for each material, with at least 10 indentation performed on each sample with 1 mm spacing. Sand particles in the size range of 75–150 μm were used for the slurry erosion studies (Fig. 1).

2.2. Slurry erosion test rig

Slurry erosion testing was performed using re-circulation type test rig shown in Fig. 2. The test rig comprised of a diaphragm pump driven by compressed air. The premixed slurry in a container is pumped using this diaphragm pump and made to impinge on a sample through 2 mm diameter tungsten carbide nozzle. The velocity of slurry jet is controlled by changing the pressure of the compressed air used for driving the pump. The test rig provides the flexibility to perform experiments at a range of different parameters such as impingement angle, particle size, stand-off distance, working media and impact velocity. The sedimentation of sand particles was prevented by continuous stirring.

2.3. Slurry erosion testing

Slurry erosion testing was conducted according to ASTM G-73 standard procedure. The test parameters used for slurry erosion experiments are shown in Table 2. Slurry with concentration of $5\ kg/m^3$ (5000 ppm) was prepared using sand (75–150 μm), mixed with tap water (pH 7.72). For each test sample, fresh slurry was used. Each sample was tested for four hours with a cycle time of one hour. Gravimetric analysis was performed using high precision weighing balance of 0.01 mg resolution. Prior to weight measurement, samples were cleaned with acetone and dried using air stream. Slurry erosion experiments were performed at a constant velocity of 20 m/s with samples positioned at different impingement angles i.e. 30°, 60° and 90°. The eroded surfaces were analyzed using scanning electron microscope (SEM) to investigate the erosion mechanism.

3. Results and discussions

3.1. Microstructural and mechanical characterization

The microstructure of the $Al_{0.1}CoCrFeNi$ HEA, SS316L stainless steel and mild steel is shown in Fig. 3. The optical micrograph of mild steel (Fig. 3a) indicates average grain size of around 30 μm. The electron back scatter diffraction (EBSD) map of the

Table 1
Nominal composition at wt% of $Al_{0.1}CoCrFeNi$ HEA, SS 316L stainless steel and mild steel used in experimentation.

Composition (wt%)	Al	Fe	Cr	C	Mn	Ni	Mo	Co	S	Si	P	Cu
$Al_{0.1}CrCoFeNi$	1.2	24.5	22.8	–	25.7	–	25.8	–	–	–	–	–
SS 316L	–	bal.	18	0.035	2	14	3	–	0.03	1	0.045	–
Mild steel	–	bal.	–	0.26	1.03	–	–	–	0.05	0.28	–	0.20